Preliminary Pebble Bed Reactor Core Dust Production Literature Review

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1 Overview of Dust production

The gas-cooled graphite-moderated pebble bed reactor is a leading concept for the Next Generation Nuclear Plant, a Very High Temperature Reactor, under consideration in the US at the Idaho National Laboratory. Currently, pebble bed reactors are being designed and planned for construction at the Tsinghua University in China.

The pebble bed reactor uses spherical graphite pebbles as fuel elements. Each pebble contains thousands of TRISO fuel particles. These pebbles are dropped into the top of the reactor, and then they travel down the reactor to the outlet chute. At the bottom of the core, the pebbles are removed and a burnup assay is performed. If the pebble has reached the burnup limit, it is sent to a storage tank. If it has not, it is recirculated again. The motion of these pebbles as they travel through the reactor produces graphite dust.

There are a variety of mechanisms for production of dust. First, there is the wear between pebbles as they travel through the reactor core. Second, is the wear between the pebbles and structural graphite. Since the hardness of the structural graphite may be different than the pebble graphite, the wear from this may be much larger than the pebble to pebble wear. Third, is the dust produced between the pebbles and various components of the fuel handling system as the pebbles are moved. Last, are non-pebble sources of dust such as oxidation from impurities in the helium. The presence of dust in the cooling system is a concern. The helium in the gas, which is used as the coolant in this reactor design, will becomes somewhat radioactive, because of tritium production from the ^3He portion. The graphite, including impurities in the graphite, and any fission products that escape from the pebbles are a major source of ionizing radiation away from the fuel elements. In addition, the dust can decrease the efficiency of the heat exchanger, and for direct cycle high temperature gas reactors the graphite particles colliding with the turbine blades will decrease their operating lifetime. There are also concerns about rapid oxidation of graphite dust in the event of an air ingress. This report concentrates only on the dust production from mechanical wear in the core.

2 Determination of dust production coefficients

There are essentially four contact wear mechanisms. Adhesive wear is from the contacting surfaces adhesively bond together, and part of the material is pulled away. Abrasive wear is when one of the contacting materials is harder than the other, and plows (or shears) away material. Fatigue wear is when the surfaces repeatedly contact each other causing fracture of the material. The last mechanism is corrosive wear, when chemical corrosion causes the surface to behave with increased wear[1]. For pebble bed reactors, adhesive wear is expected to be the dominate wear mechanism.

As a first order approximation the adhesive dust production volume is:

$$V = K_{ad}\frac{N}{H}L \tag{1}$$

In this equation V is the wear volume, K_{ad} is the wear coefficient for adhesive wear, L is the length slide and $\frac{N}{H}$ is the real contact area (with N the normal force and H the hardness)[1]. Typically, the hardness and the wear coefficient for adhesive wear are combined with the units of either mass or volume over force times distance. For two blocks, the length slide is the distance that one of the blocks travels over the other while in contact. Note that this formula is only an approximation since the wear volume is only approximately linear with respect to both the normal force and the distance traveled. Abrasive wear also can be approximated by this model, but fatigue and corrosive will not be modeled well by this. To the extent that these wear mechanisms are present in the pebble bed reactor, this model may also be less valid.

The wear coefficient is typically measured by grinding or stroking two pieces of graphite against each other, and then measuring the decrease in mass. The details of the experiment such as the contact shape and the orientation of the relative motion affect the wear coefficient.

The wear that occurs with graphite depends on multiple factors. A partial list includes the normal force of contact (load), the temperature of the graphite and the past wear history (since wear tends to polish the contact surfaces and remove loose grains). The atmosphere that the graphite is in affects the wear rates since some molecules chemically interact with the carbon or are adsorbed on the surface. Neutron damage and other radiation effects can damage the structure of the graphite and affect the wear. The type and processing of the graphite can affect wear rates. As a related effect, if harder and software graphites interact, the harder one can 'plow' into the softer and increase wear rates.

For graphite on graphite, depending on conditions there can be over three orders of magnitude difference in the wear. For example graphite on graphite in air at room temperature can exhibit wear rates of 3.3e-8 g/(Nm)[2] but in the dusting regime at 200°C the wear coefficient can be 2e-5 g/(Nm)[3], which is about a thousand times greater[1]. For this reason, conditions as close to the in core conditions are needed for determining a better approximation of the wear coefficients.

For tests using nuclear graphite near in-core conditions, the best data available to the authors is from two independent sets of experiments. One dataset emerged from the experiments by O. M. Stansfield[18] and the other is from a series of experiments performed at the Tsinghua University[2, 4, 5].

O.M. Stansfield measured friction and wear with different types of graphite in helium at different temperatures[18]. In the experiments, two pieces of graphite were slide against each other linearly with a 0.32 cm stroke. Two different loads were used, one 2-kg mass, and another 8-kg mass. The data for wear volumes is only provided graphically, that is not tabulated, therefore only order of magnitude results are available. The wear values were about an order of magnitude higher at 25°C than at 400°C and 800°C. There was a reduction of friction with increased length slide, but no explanation was provided[2]. Typical values for the wear rates are 10e-3 cm^3/kg for the 25°C case and 10e-4 cm^3/kg for the 400°C and 800°C for 12 500 cm distance slide. With a density of 1.82 g/cm^3, these work out to about 1.5e-6 g/(Nm) and 1.5e-7 g/(Nm). These are only about an order of magnitude above room temperature wear.

The second set of experiments were done at the Tsinghua university. The first paper measures the wear coefficient of graphite KG-11 via pressing a static specimen against a revolving specimen. The wear is measured by weighing the difference in mass before the experiment and after the experiment. At room temperature in air they measured wear rates of 7.32e-9 g/(Nm) with 31 N load with surface contact, 3.29e-8 g/(Nm) with 31 N load with line contact and 3.21e-8 g/(Nm) with 62 N load[2]. The second paper measures the wear coefficient of graphite IG-11 on graphite and on steel at varying loads[4]. Unfortunately, there are inconsistencies in the units used

[1] In air, above a certain temperature graphite wear transitions to dusting wear, which has much greater wear rates. Increased water vapor decreases or eliminates the dusting wear.

[2] Possibly this was due to a lubrication effect or the removal of rough or loose surfaces.

in the paper. For example, in Table 2 the mean wear rate for the lower specimen is listed as 3.0e3 μg/m, but in the text it is listed as 0.3e-3 μg/m, seven orders of magnitude different. The 30 N of load upper specimen wear coefficient for the first 30 minutes is listed as 1.4e-3 μg/m, which works out to 4.7e-10 g/(Nm). If 1.4e3 μg/m is used, this works out to 4.7e-4 g/(Nm). Neither of these matches the first paper's results. First, it seems that the units of μg, (or micrograms or 1.0e-6 g) are used where mg (or milligrams or 1.0e-3 g) should be. The second inconsistency is in the sign for the exponent, when sometimes the negative sign is dropped. These two mistakes would make the correct exponents 1.0e-3 mg/m and the measured coefficient 1.4e-3 mg/m or 4.7e-7 g/(Nm), which match reasonably well to the first paper's values on the order of 1.0e-8 g/(Nm). For the rest of this report, it is assumed that these corrections should be used for the Xiaowei Luo et al. papers.

The third paper measures the temperature effects in helium[5]. The experimental setup is similar to the setup in the second paper, but the atmosphere is a helium atmosphere and the temperatures used are 100°C to 400°C with a load of 30 N. In Fig 2. of that paper, it can be qualitatively determined that as the temperature increases, the amount of wear increases. As well, the wear tends to have a higher rate initially, and then decrease. Since the wear experiment was performed using a 2 mm long stroke, it seems plausible that wear rates in an actual pebble bed might be closer to the initially higher rates since the pebble flow might be able to expose more fresh surfaces of the pebbles to wear. From the graph, there does not seem to be a clear trend in the wear as a function of temperature. This makes it difficult to estimate wear rates since pebble bed reactor cores can have temperatures over 1000°C in normal operation. The highest wear rate in Table 2 of the paper is 31.3e-3 mg/m at 30 N, so the highest wear rate measured is 1.04e-6 g/(Nm). This is about 20 times lower than wear in the dusting regime. Since the total amount of wear (from Fig. 2) between 200°C and 400°C roughly doubles in the upper specimen and increases by approximately 35% in the lower specimen, substantially higher wear rates in over 1000°C environments are hard to rule out. Note however that the opposite trend was observed in the Stansfield paper.

3 Calculation of Force in Reactor Bed

In order to calculate the dust produced in the reactor, the force acting on the pebbles in needed. Several different approximations can be used to calculate this with varying accuracy. The simplest (but least accurate) method of approximating the pressure in the reactor is using the hydrostatic pressure, or

$$P = \rho f g h \tag{2}$$

where P is the pressure at a point, ρ is the density of the pebbles, f is the packing fraction of the pebbles (typical values are near 0.61 or 0.60), g is the gravitational acceleration and h is the height below the top of the pebble bed. With knowledge of how many contacts there are per unit area or per unit volume, this can be converted into pebble to surface or pebble to pebble contact forces. This formula is not correct when static friction occurs since the static friction allows forces to be transferred to the walls. Therefore, Equation 2 over-predicts the actual pressures in the pebble bed.

In the presence of static friction, more complicated calculations are required. The fact that static friction transfers force to the wall was observed by the German engineer H.A. Janssen in 1895[6]. Formulas for the pressure on the wall for cylindrical vessels with conical exit chutes were derived by D.M. Walker[7]. Essentially, when the upward force on the wall from static friction for a given segment matches the downward gravitational force from the additional pebbles in that segment, the pressure stops increasing.

For a cylinder, the horizontal pressure equation is[8]:

$$P_h = \frac{\gamma D}{4\mu_w}\left[1 - \exp\left(\frac{-4\mu K}{D}x\right)\right] \tag{3}$$

where γ is the bulk weight (or $f\rho g$), D is the diameter of the cylinder, μ_w is the static friction coefficient between the pebbles and the wall, K is the Janssen

Coefficient, and x is the distance below the top of the pile.

The Janssen coefficient is dependent upon the pebble to pebble static friction coefficient and can be calculated from:

$$K = \frac{1 - \sin\phi}{1 + \sin\phi} \tag{4}$$

where $\tan\phi = \mu_p$ and μ_p is the pebble to pebble static friction. Since $\tan^{-1}\mu = \sin^{-1}\left(\frac{\mu}{\sqrt{\mu^2+1}}\right)$ then K can also be written as:

$$K = 2\mu_p^2 - 2\mu_p\sqrt{\mu_p^2 + 1} + 1 \tag{5}$$

The Janssen formula derivations make assumptions that are not necessarily true for granular materials. These include assuming the granular material is a continuum and that the shear forces on the wall are at the Coulomb limit[9]. The static friction force ranges from zero at first contact up to μN (the Coulomb limit) when sufficient shear force has occurred. If the force is not at the Coulomb limit, then an effective μ may be able to be found and used instead. In general, this assumption will not be the case when the pebbles are freshly loaded since they will not have slid against the wall enough to fully load the static friction. Even after the pebbles have been recirculated, they may not reach the Coulomb limit and effective values for the static friction constant may be needed instead for predicting the wall pressure. Finally, real reactors have more complicated geometries than a smooth cylinder above a cone exit chute.

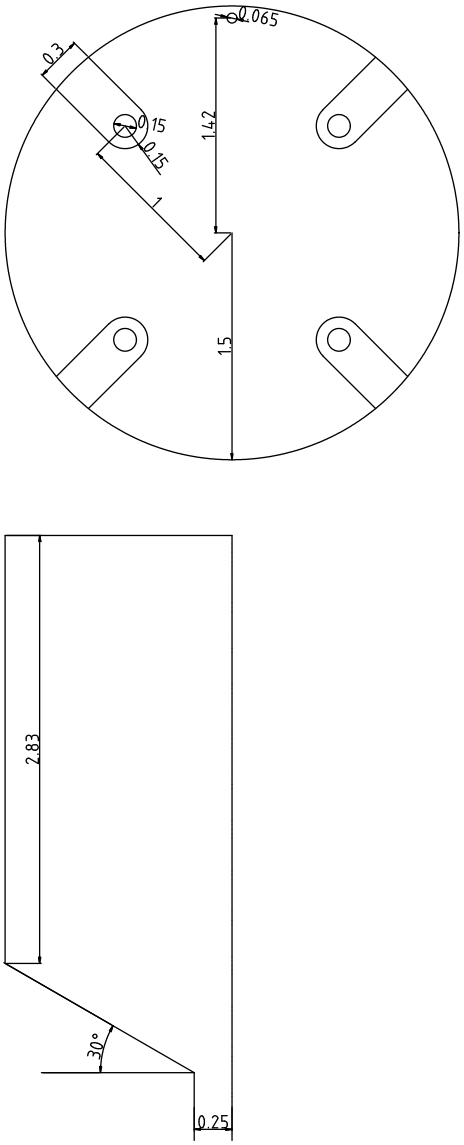

Figure 1: AVR dimensions

4 Prior data on dust production

The 46 MW thermal pebble bed reactor Arbeitsgemeinschaft VersuchsReaktor (AVR) was created in the 1960s in Germany and operated for 21 years. The pebbles were added into the reactor through four feeding tubes spaced around the reactor and one central feeding tube at the top of the reactor. There was one central outlet chute below. Into the reactor cavity there were four noses of U shaped graphite

Table 1: AVR Data

Name	Value
Average Inlet Temperature	250°C
Average Outlet Temperature	950°C
Pebble Circulation Rate	300-500 per day
Dust Produced	3 kg per year
Pebbles in Reactor Core	100,000
Reactor Radius	1.5 m
Outlet Chute Radius	0.25 m
Angle of Outlet Cone	30°
Control Rod Nose Thickness	0.3 m
Radius of Control Rod Nose	0.15 m
Feed tube to outlet chute	2.83 m

with smooth sides for inserting the control rods. The cylinder walls contained dimples about 1/2 a pebble diameter deep and that alternated location periodically. All the structural graphite was a needle coke graphite. Dimensions are shown in Figure 1 and design and measured data is provided in Table 1. The measured dust production rate was 3 kg per year. No real conclusions were inferred because of a water ingress, an oil ingress, the uncertainity in the composition of the dust (i.e., metallic components) and the uncertainty of the location of dust production [10, 11]. The interior of the AVR reactor reached over 1280°C as determined by melt wire experiments[12].

The THTR-300 reactor was a thorium and uranium powered pebble bed reactor that first went critical in 1983 and ran through 1988. THTR-300 produced 16 kg of dust per Full Power Year (FPY), and an estimated 6 kg of that was produced in the core of the reactor[13]. The fuel rods in the THTR-300 actually pushed into the pebble bed. On a per pebble basis, the amount of dust produced in the THTR-300 is lower than in the AVR. Further data on the THTR-300 is summarized in Table 2[14, 15].

5 Prior Prediction Work

There are two papers published that attempt to predict the in core pebble dust production. The first paper is "Estimation of Graphite Dust Quantity and Size Distribution of Graphite Particle in HTR-10"

Table 2: THTR Data

Name	Value
Average Inlet Temperature	250°C
Average Outlet Temperature	750°C
Core Height	6.0 m
Pebbles Circulated	1,300,000 per FPY
Core Diameter	5.6 m
Pebbles in Full Core	657,000
Total Dust Produced	16 kg per FPY
Estimated In Core Dust	6 kg per FPY

and was created to estimate the dust production that the core of the HTR-10 reactor would produce. The second is by this paper's authors and attempts to estimate the dust that the AVR reactor produced.

The HTR-10 paper started by calculating from the hydrostatic pressure the force between the pebbles at the bottom of the reactor. The force was approximated to be 30N. The remainder of the paper uses 30N as the force for conservatism. Note that the HTR-10 paper is in Chinese, so this literature review may contain mistakes in understanding due to language differences.

The dust production is calculated in three regions, the core of the reactor, the outlet chute of the reactor and the fuel loading pipe. As with the other papers, the assumption is made that μg should actually be mg.

For the core of the reactor the temperature used is 550°C with pebble to pebble wear rates of 4.2×10^{-3} mg/m extrapolated from 400°C data. The pebble to wall wear rates are extrapolated to 480°C to 12.08×10^{-3} mg/m from the 400°C data. The pebble to pebble wear is estimated to occur for 2.06 m[3] and 3.85% of pebbles are estimated to wear against the wall. From this data the average pebble dust production per pass in the core is determined to be 8.65×10^{-3} mg for pebble to pebble wear and 0.99×10^{-3} mg from pebble to wall. The total in-core graphite dust produced per pebble pass is 9.64×10^{-3} mg.

The outlet chute wear is estimated to occur for

[3]This is the length slide and is multiplied by 4.2×10^{-3} mg/m to get per pass dust production

2.230 m in the graphite portion and 1.530 m in the stainless steel portion, and that 44.16% of the pebbles wear against the chute. Both these portions are estimated to be at 400°C. Wear rates of 3.5×10^{-3} mg/m are used for the pebble to pebble wear, and 10.4×10^{-3} mg/m for the pebble to graphite chute and 9.7×10^{-3} mg/m for pebble to steel. Thus for the outlet chute the upper portion has 18.05×10^{-3} mg of dust produced per average pebble and the lower portion has 11.91×10^{-3} mg produced for a total outlet chute amount of 29.96×10^{-3} mg.

The fuel loading pipe is approximately 25 m long and the temperature is 200°C which gives a wear value of 2.1×10^{-3} mg/m and 52.50×10^{-3} mg. Thus, for an estimated average pebble pass, 10.5% of the dust is produced in core, 32.5% is produced in the outlet chute and 57.0% is produced in the loading pipes. The paper estimates that 50% of the outlet chute graphite dust enters the core and that 75% of the graphite dust produced in the fuel loading pipes enters the reactor core, for a total amount of graphite dust entering the core of 64.0×10^{-3} mg per pebble pass. Since there are 125 pebbles entering the reactor a day, and 365 days in a year, this works out to 2.92 g/year of pebble dust per year (reported in the paper as 2.74 kg/year due to a precision loss and unit errors)[16].

HTR-10 has 27 thousand pebbles compared to AVR's 100 thousand and a rate of 125 pebbles per day compared to about 400 pebbles per day. A crude scaling factor estimate of 35 grams of dust per year would be produced per year in AVR. Measured values of dust generation rates from HTR-10 would provide valuable information on pebble bed reactor dust production but appear to be unavailable.

The other dust production paper available is written by this report's authors[17]. The pebbles in the AVR reactor core were simulated using the PEBBLES discrete element code, and force times distance tallies were constructed. The code calculated that per pass the average pebble would experience 802.2 Nm of wear from pebble to pebble and 23.9 Nm of wear from pebble to wall contact. For lack of better data, the paper used the air graphite wear coefficient of 3.290e-8 g/Nm from Sheng et al. With this coefficient, the yearly dust production from AVR was estimated as 4 grams. A large part of the dust was produced where the outlet chute begins due to higher pressures from bridge like structures developing that concentrating the force where the wall transition to the output chute. Like the HTR-10 paper,this paper made simplifying assumptions. The wall indentations or dimples and the control rod nose cones were not modeled. In addition, the fuel handling equipment was not modeled. If a larger graphite coefficient, 1.04e-6 g/(Nm), is used (the highest reported in the Xiaowei helium graphite on graphite experiments) the model predicts 126 grams of graphite dust in the reactor. The AVR reactor was operated at a higher temperature than the HTR-10, so it is possible that the difference in estimates of dust production come from higher wear coefficients. The paper concludes that graphite wear data at additional temperatures was needed before the AVR in core dust production could be modeled.

6 Open Questions

The values of graphite wear coefficients in the full range of pebble bed reactor conditions are unknown. Without these coefficients, reliable predictions of graphite dust production quantities are not possible. The amount of dust produced in these cores (even order of magnitude estimates) is one of the key questions that need to be answered. Is AVR dust production typical or was it a consequence of the particular operation of this experimental facility? Are larger reactors expected to produce even more quantities of dust? If not, then dust production may be less of a problem than has been envisioned. There is still significant uncertainty on the severity of the dust production and its consequences in pebble bed reactors.

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8 Disclaimer

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